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Article

Effects of a Dual-Task Paradigm and Gait Velocity on Dynamic Gait Stability during Stair Descent

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Featured Application: The authors concluded that the influence of gait velocity should be considered when assessing the effects of dual-tasks. Understanding the effects of the interaction between the dual-task paradigm and gait velocity on dynamic gait stability may provide new insights into a dynamic postural control mechanism.

Abstract: Falls during stair negotiation have become one of the leading causes of accidental death. The effects of a concurrent cognitive or manual dual-task paradigm on dynamic gait stability remain uncertain. How much dynamic gait stability is influenced by gait velocity is also not clear. A total of 16 healthy young females descended a staircase under three different walking conditions: descend stairs only (single task), descend stairs while performing subtraction (cognitive dual-task), and descend stairs while carrying a glass of water (manual dual-task). An eight-camera Vicon motion analysis system and a Kistler force plate embedded into the third step of the staircase were used synchronously to collect kinematic and kinetic data. Gait velocity decreased and dynamic gait stability increased with both cognitive and manual dual-task conditions. The center of mass–center of pressure inclination angle increased with gait velocity but decreased with the manual dual-task condition compared to the single-task condition. Changes in gait velocity caused by the dual-task paradigm can partially explain the effects of dual-task dynamic gait stability. The influence of gait velocity should be considered in the assessment of dual-task effects.

Keywords: manual task; cognitive task; dynamic balance; posture control; stair negotiation

1. Introduction

Stair negotiation is an activity of daily living with the potential for falls. Falls on stairs account for 26% of all self-reported falls [1] and are one of the leading causes of accidental death [2]. Compared with stair ascent and level walking, stair descent accounts for 75% of falls on stairs [3] and demands greater lower-limb joint range of motion [4] and muscle strength [5]. Stair descent imposes significant challenges to dynamic gait stability (DGS) in people of all ages [6].

Dual-tasking is essential to daily living activities, including during stair descent [7]. The simultaneous performance of additional tasks often results in changes in gait patterns that are associated with falls [8]. A dual-task involves performing a physical task (e.g., movement or walking) while performing a

concurrent cognitive (CT) or manual (MT) task. Gait changes and concurrent dual-tasking are strongly associated when the gait task is challenging, like during stair descent [9]. Previous studies revealed different dual-task effects on DGS. Some reported that CT or MT adversely affected stability [10,11], while others showed that it might help stabilize gait [12,13].

A possible explanation for the inconsistent results is the different variables used to measure DGS, including center of mass (COM) displacement, center of pressure (COP) displacement, or COM–COP separation. COM displacement represents the degree of body sway in different directions [14]. COP displacement, calculated by the position changes of the point of ground reaction forces [15], represents gait strategy and body stability [16]. COM–COP separation represents the ability during gait to control COM motion from the COP beneath the feet within appropriate limits [17]. Increased COM, COP displacement, and COM–COP separation were all interpreted as a decrease of DGS during stair descent [14,16,17]. COM–COP inclination angle (IA), formed by the vertical line and the projection of the vector onto the sagittal and frontal planes [18], was proposed to provide a more comprehensive assessment than the examination of COM or COP [19]. IA can better represent instability than COM or COP measures [19] and better include the influence of leg length or body height than COM–COP horizontal separation [20]. IA considers both COM and COP, thereby providing a useful description of the relationship between the body and base of support [19]. Greater IA leads to an increase in moment arm of force, which further results in an increase in inertia and momentum of the body segments for balance recovery [19]. The greater the IA, the further the COM diverges from the COP, and the more difficult it is to bring the COM above the COP [21]. If the COM and COP become separated extensively and consequently prevent the lower-limb joint moments from supporting upright posture, a fall can occur [22]. IA has been extensively used to measure the DGS during level walking [23,24], treadmill walking [20,24], narrow-heeled walking [21], obstacle crossing [23,25], and golf swing [26], and was claimed as an effective representation of DGS [20]. However, it has rarely been used to examine DGS during one of the most hazardous locations for fall accidents [27], stair descent.

Changes in gait velocity caused by a dual-task paradigm may be another reason for the reported DGS differences. Some considered velocity when they tried to confirm the influence of a dual-task on DGS; others did not. Even the ones that considered velocity reported conflicting results. Lu et al. (2017) reported that the velocity increase associated with young adults could cause a significant increase in IA [18], while Chien et al. (2013) considered that gait velocity did not impose a limitation on the interpretation of the IA [21]. Although IA may change with changes in gait velocity and dual-task performance, few studies examined the association among gait velocity, dual-task performance, and IA.

In a dual-task paradigm, the introduction of a concurrent task during cognitive or motor performance leads to possible competition [28] or integration [13] between the attentional resources available. The ability to maintain balance under dual-task conditions relies on the efficiency of attentional resources, which control both gait and performance of the concurrent CT or MT. Thus, research utilizing dual-task paradigms can provide important insights into the interactions between cognition and gait control. Furthermore, understanding the effects of the interaction between the dual-task paradigm and gait velocity on DGS may provide new insights into a dynamic postural control mechanism. The primary purpose of this study was to examine the relationship between velocity and a dual-task performance on DGS during stair descent. The secondary purpose was to address the importance of gait velocity in assessing the effects of a dual-task. We hypothesized that velocity would decrease under dual-task conditions, a concurrent dual-task condition would adversely affect DGS during stair descent, and DGS would decrease with increasing gait velocity under a dual-task paradigm during stair descent.

2. Materials and Methods

2.1. Participants

Power analysis (G*Power Version 3.1) indicated that the sample size requirement for 80% statistical power was 11. A total of 16 healthy young females participated in this study (age: 21.6 ± 2.19 years old; height: 162.4 ± 4.7 cm; body mass: 53.4 ± 6.7 kg). Exclusion criteria included the inability to follow instructions, unstable heart conditions, lower-limb joint replacement, arthritis, diabetes, visual deficits, vestibular deficits, or any other neuromuscular problems that could prevent participants from executing the experimental protocol safely and effectively. Participants did not take any medication in the preceding six months and reported having no fall experience or gait abnormalities in the preceding three years. They were all right-foot dominant, defined as the preferred leg for kicking a football [29]. All participants signed written informed consent forms before participation. The project was approved by the Shandong Sport University Ethical Review Board in accordance with the Declaration of Helsinki (20180026).

2.2. Apparatus

A staircase with six steps was constructed for data collection. The step dimensions were 17.0×29 cm for riser and tread, respectively. One force plate (Kistler, 9287BA, Winterthur, Switzerland) was embedded into the third step of the staircase, and the ground reaction force was collected at 1000 Hz. An eight-camera motion analysis system (Vicon, Oxford Metrics Ltd., Oxford, UK) was used for kinematic data collection at 100 Hz. The force and kinematic data collection were synchronized using the Vicon system. More details can be found in our previous report [30].

2.3. Study Protocol and Data Collection

All the participants were instructed to descend the staircase step-over-step under three conditions: 1) single task (ST, descend stairs only); 2) cognitive dual-task (CT, descend stairs while subtracting serial threes from a three-digit number); and 3) manual dual-task (MT, descend stairs while carrying a glass filled with 350 mL of water in their right hand). Testing conditions were randomized. The participants practiced each condition before data collection. Data from five successful trials were collected and three trials were extracted for further analysis. A trial was considered successful when the participant continuously descended from the top to the bottom of the staircase and then continuously walked for 10 m. There was a one-minute rest between trials.

2.4. Data Analysis

All kinetic and kinematic data were obtained from a right foot single-support phase between the left toe lifting off the fourth step and the left toe contacting the second step (1a). The single-support phase was normalized to 100 equal time intervals. COM was obtained from a 13-segment whole body model using the Vicon Plug-In Gait model. Gait velocity was calculated as $\Delta x / \Delta t$, where Δx is the displacement of COM and Δt is the time between the two normalized time intervals. Peak velocity was represented by the maximum absolute value of the gait velocity during the single-support phase. The COP position was calculated using forces measured by the force plate. The anterior (+)/posterior (−) positions of the COM and COP are described parallel to the direction of progression. The medial (left)/lateral (right) positions of COM and COP are described relative to the line of progression [31] (Figure 1b). IA was determined as the instantaneous orientation of the line connecting the COM and COP with respect to a vertical line through the COP [23]; IA in anterior/posterior and medial/lateral was calculated correspondingly (see below). In this study, we examined the maximum IA during a single-support phase, an unstable period in which one can easily fall [22]. COM and COP data were filtered with fourth-order low-pass Butterworth filters with cut-off frequencies of 7 Hz [32] and 50 Hz [33], respectively.

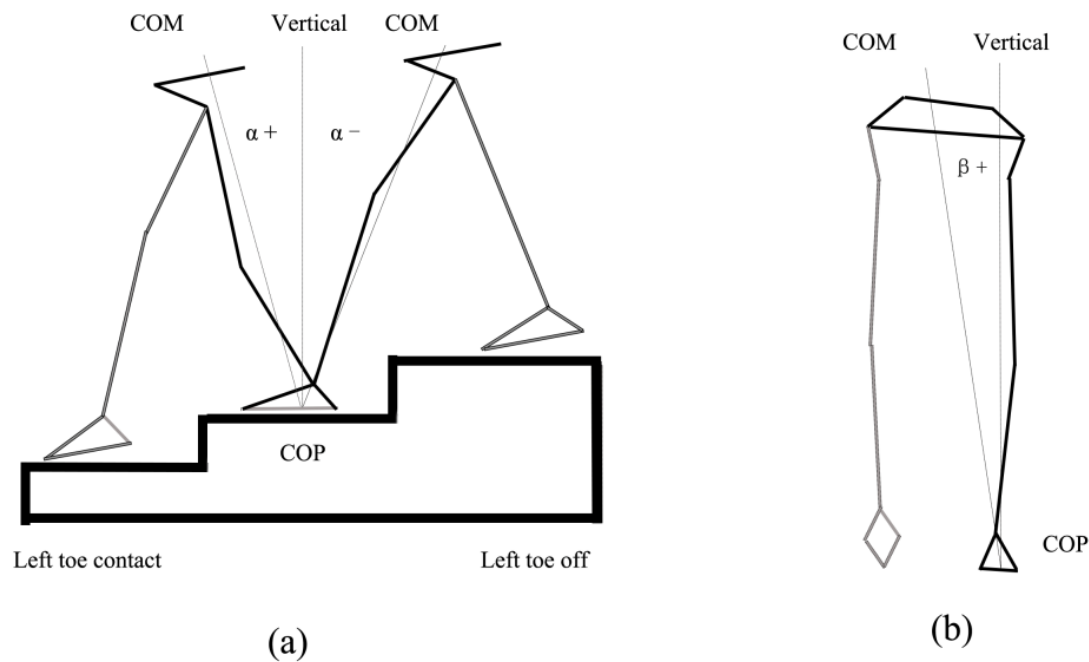


Figure 1. (a) Graphical representation of the right foot single-support phase beginning with the left toe-off the fourth step of the staircase and ending with the left foot contacting the second step, also showing the anterior/posterior center of mass (COM)–center of pressure (COP) inclination angle α . (b) The medial/lateral COM–COP inclination angle β .

The anterior/posterior IA (α) and the medial/lateral IA (β) were calculated as follows [21]:

$$\vec{t} = \frac{\vec{P}_{\text{COM-COP}} \times \vec{P}_{\text{vertical}}}{\vec{P}_{\text{COM-COP}}} \quad (1)$$

$$\alpha = \sin^{-1}(t_x) \quad (2)$$

$$\beta = \sin^{-1}(t_y) \quad (3)$$

where $\vec{P}_{\text{COM-COP}}$ is the vector pointing from COP to COM, and $\vec{P}_{\text{vertical}}$ is the unit vector of the vertical axis of the global coordinate system.

2.5. Statistical Analysis

Gait velocity and IA normality were tested using the Shapiro–Wilk test. One-way repeated-measures ANOVAs were employed to examine the first and second hypotheses. Multiple regression analysis was used to predict the independent variables of IA (y) based on the dependent variable of velocity (x) during ST, CT, and MT conditions. Categorical variables were used to indicate the various conditions with the values set to $A = 0/B = 0$, $A = 1/B = 0$, and $A = 0/B = 1$ for the ST, CT, and MT conditions, respectively. Regression analysis was conducted for IA in the anterior/posterior and medial/lateral directions separately. The full regression model was

$$y = a_0 + b_0x + Aa_1 + Ab_1x + Ba_2 + Bb_2x + e \quad (4)$$

where a_0 , a_1 , a_2 , b_0 , b_1 , and b_2 are regression coefficients; A and B are dummy variables denoting different conditions; and e is the error term. Dummy variables in this regression analysis procedure were used to distinguish regression equations under different conditions.

A stepwise forward elimination procedure was used to determine the optimum regression equation in each condition. For a term to be retained, the term should significantly contribute to the prediction of y ($p < 0.05$). The collinearity of the variables was checked simultaneously, and it was confirmed if the variance inflation factor (VIF) was greater than 3.

3. Results

The Shapiro–Wilk test indicated that all the dependent variables were normally distributed ($p > 0.05$). Figure 2 presents the gait velocity magnitude traces of the different conditions. Velocity decreased from left toe-off and reached its lowest point at about 35% of the single-stance phase before increasing to a greater value. One-way repeated measures ANOVA for peak velocity revealed significant condition differences ($p < 0.001$). Post hoc analysis indicated that the peak velocities under CT ($p = 0.003$) and MT ($p < 0.001$) dual-task conditions were significantly lower than that under ST ($CT_{\text{velocity}} = 0.79 \pm 0.09$; $MT_{\text{velocity}} = 0.68 \pm 0.08$; $ST_{\text{velocity}} = 0.91 \pm 0.11$ m/s). Peak velocity was also lower in MT than in CT ($p = 0.001$).

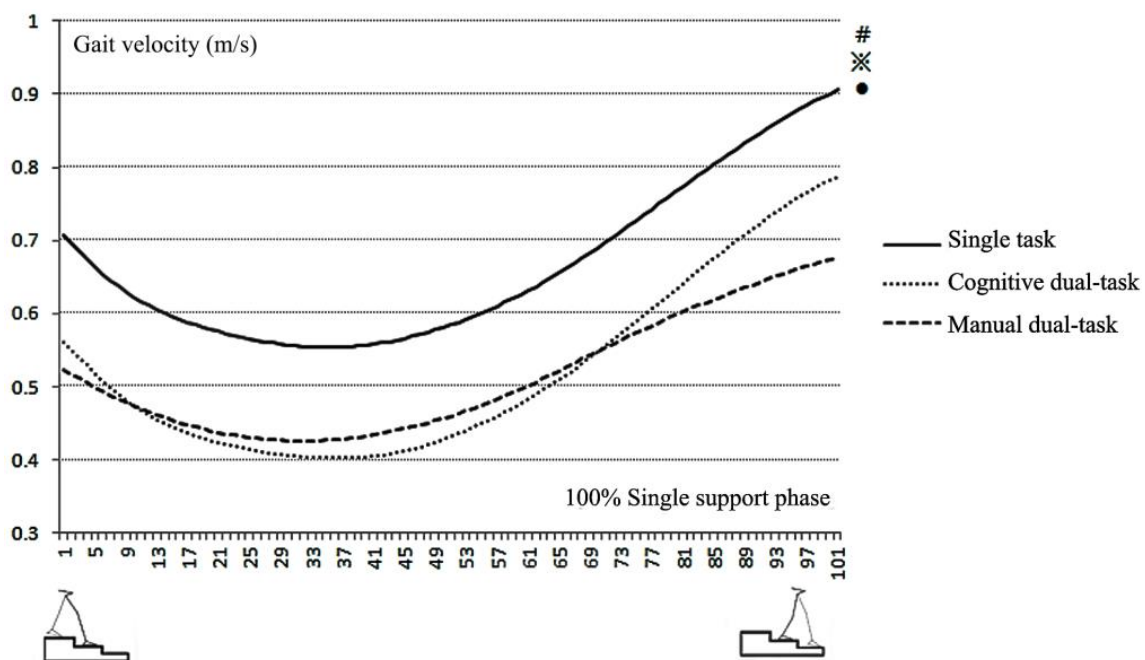


Figure 2. Descending velocity (y) of the single-support phase (x) during single-task and cognitive and manual dual-task conditions; # Significant difference between single-task and cognitive dual-task conditions; * Significant difference between single-task and manual dual-task conditions; • Significant difference between cognitive and manual dual-task conditions.

Figure 3 presents the IA traces during stair descent. Figure 3a indicates that $IA_{A/P}$ increased from a negative value to a positive value during the right foot single-support phase, indicating that COM was behind the COP at the beginning but ahead at the ending. An IA peak was observed during left toe contact. A repeated-measures ANOVA indicated a significant condition effect ($p < 0.001$). Post hoc analysis revealed that the peak $IA_{A/P}$ was less under the CT and MT dual-task conditions ($CT_{A/P} = 8.29 \pm 0.82^\circ$, $p = 0.019$; $MT_{A/P} = 7.16 \pm 0.89^\circ$, $p < 0.001$) than under the ST ($ST_{A/P} = 9.05 \pm 0.79^\circ$). The peak $IA_{A/P}$ was also less under MT than under CT ($p < 0.001$).

In Figure 3b, $IA_{M/L}$ decreased from left toe-off, then increased to a much greater value during the single-support phase. A positive value indicated that the COP was lateral (on the right) to the COM. A repeated-measures ANOVA revealed a significant condition effect ($p = 0.020$). Post hoc analysis revealed that the peak $IA_{M/L}$ during MT ($MT_{M/L} = 5.95 \pm 1.02^\circ$, $p = 0.020$) was less than that during ST ($ST_{M/L} = 6.49 \pm 0.53^\circ$).

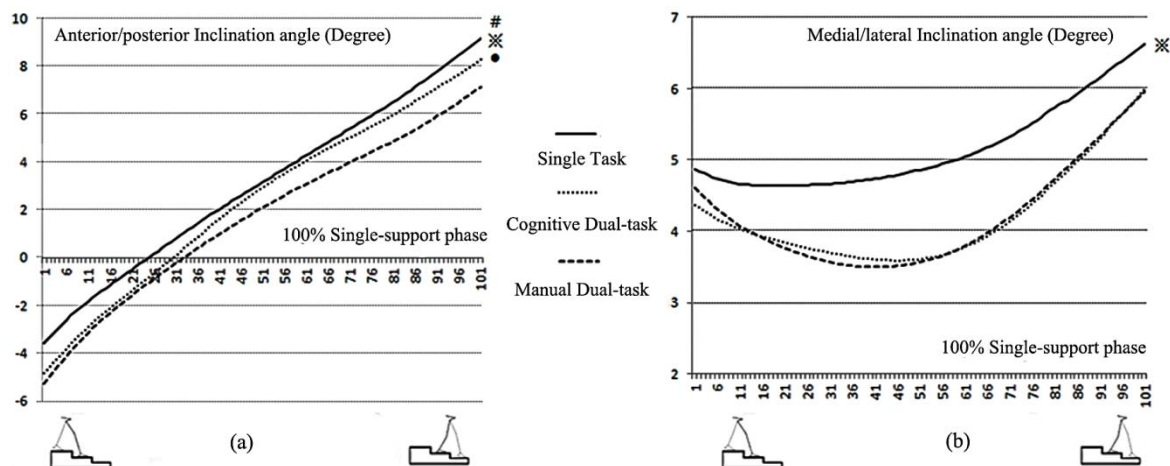


Figure 3. COM-COP inclination angles (y) of the single-support phase (x) in the (a) anterior/posterior and (b) medial/lateral directions; # Significant difference between single-task and cognitive dual-task conditions; * Significant difference between single-task and manual dual-task conditions; • Significant difference between cognitive dual-task and manual dual-task conditions.

During the stepwise forward elimination procedure of peak $IA_{A/P}(y)$ as a function of peak velocity (x), A and Ax were excluded with p-values of 0.591 and 0.645, respectively, and Bx was excluded with a VIF of 59.289. The best regression equation was expressed as follows:

$$y = 4.976 + 4.365x - 0.768B. \quad (5)$$

The regression determinant (r^2) was 0.689 ($p < 0.001$). The equation indicates that the faster the peak velocity, the greater the $IA_{A/P}$. The effect of gait velocity on $IA_{A/P}$ within the corresponding range of variation in this study was 2.925° (the difference between the maximum and minimum velocity multiplied by the regression coefficient). Concurrent MT decreased $IA_{A/P}$ with a magnitude of 0.768° , whereas concurrent CT did not influence $IA_{A/P}$.

During the stepwise forward elimination procedure of the peak $IA_{M/L}(y)$ as a function of peak velocity (x), A, B, Ax, and Bx were excluded with p-values of 0.674, 0.956, 0.497, and 0.921, respectively. The best regression equation was expressed as follows:

$$y = 4.115 + 2.712x. \quad (6)$$

The regression determinant (r^2) was 0.160 ($p = 0.005$). The equation showed that the faster the peak velocity, the greater the $IA_{M/L}$. The effect of peak velocity on $IA_{M/L}$ within the corresponding variation range in this study was 1.817° . Concurrent MT or CT did not affect the peak $IA_{M/L}$.

4. Discussion

This work is the first known research to investigate the effect of a concurrent dual-task condition on gait velocity and DGS, represented by IA, one of the potential indicators for DGS, during stair descent. The main observations in this study were threefold. First, peak gait velocity decreased under concurrent cognitive (CT) or manual (MT) dual-task conditions. Second, DGS was adversely affected by a concurrent dual-task; and finally. Third, IA was positively related to gait velocity and negatively related to a concurrent MT.

Agreeing with previous literature, the results here showed that maximum gait velocity during a single-limb stance decreased during dual-task stair descent. Previous research on the effect of dual-task paradigms during stair negotiation on DGS using the COM range of motion reported a decrease in velocity during stair descent/ascent among young males [9]. It has also been reported

that velocity decreased under dual-task conditions during level walking for both young [34] and old participants [7,10]. Here, the maximum gait velocity was greater under ST than under CT/MT.

It was once believed that gait occurs unconsciously and does not involve higher brain functions such as attentional resources. However, a consensus has been reached that CT and MT require attentional resources [9,28,35–37]. Under dual-task conditions, attentional resources are split and allocated to each task, and the concurrent task draws attentional resources away from gait [9]. Dual-tasks appear to cause a performance decrement in at least one of the components of the dual-task. Previous studies have indicated that dual-task changes in gait might result from a competition between the attention demands of gait and the concomitant dual-task [30]. This study corroborates previous findings that a dual-task paradigm affected gait velocity.

Although the paradigms were observed to influence gait velocity adversely, this does not mean that they would negatively influence DGS evaluated as IA. IA was hypothesized to be adversely affected by CT/MT when compared to ST. However, our results failed to support our second hypothesis in both the anterior/posterior and medial/lateral directions; the decreased IA indicates improved DGS under CT or MT conditions during stair descent. These results are consistent with most previous young participant research, which reported additional stabilization rather than postural destabilization occurring during a concurrent dual-task paradigm [12,13,37,38]. One study was reported that showed worse DGS under dual-task conditions among young males in terms of COM medial/lateral range of motion [9]. The differences between our study and theirs may stem from the different DGS measurements. Their dependent variable was the COM range of motion, which does not necessarily indicate instability [19].

The unique effects of dual-tasks on DGS should be studied without the influence of gait velocity. Thus, stepwise forward elimination multiple regression analyses were performed to determine and compare the relationships between velocity, dual-task condition, and DGS. The third hypothesis was supported since the results showed that DGS decreased with increasing gait velocity under both the MT and CT paradigms. Two previous studies published by our group reported that IA was increased under a relatively faster velocity condition during over-ground [18] and treadmill walking [20].

The regression analyses also indicated that concurrent MT decreased IA in the anterior/posterior direction with a magnitude of 0.768° , which means that concurrent MT increases DGS. Our results agree with some previous studies [12,13] indicating integration between attentional resources. It is worth mentioning that one study with similar results speculated that the constraint imposed by the more demanding dual-task condition interplayed with the original gait task (stair descent), leading to improved body stability [13]. Further evidence for this conceptualization has been provided through neurophysiological measurements demonstrating increased activation of the supplementary motor area and primary sensorimotor areas during a dual-task condition [39]. Activities of the supplementary motor area and the primary sensorimotor areas during the dual-tasks employed here need to be investigated in future projects. Since improved body stability is a prerequisite for stable maintenance of glass-holding, it is plausible that the performance of the original task also benefited [13]. These results have been interpreted to be a consequence of the functional integration of postural control with a dual-task paradigm. To be specific, the functional integration between gait and MT is implemented as the control of not two independent units but a single unit in a coordinated task. This conceptualization could also help explain why MT was related to DGS but not CT. Since MT and gait are both motor-related tasks, they may be easily integrated as a single unit, while the integration of a cognitive task and a gait task as in CT may be much more difficult. The possibility worth mentioning here is that a cautious gait strategy could have been employed to avoid spilling water rather than to prevent a fall.

The authors recommended that future studies concerning the dual-task paradigm should consider the gait velocity and differentiate the effects of MT and CT, since they may differently influence the concurrent task. This study was conducted with a group of young females for proof of concept. Future studies should focus on the elderly population since they experience more falls [40] and require more attentional resources during stair ambulation [41] compared to their younger counterparts.

This study has several limitations. Firstly, it would be a good option if we could measure the DGS in different gait velocities (like normal and fast) since this work aimed to examine the effects of gait velocity on DGS during stair descent. However, it would be difficult for the participants to maintain a fast gait velocity when they were asked to perform a concurrent cognitive task. There would be an apparent decrease in gait velocity when they started to calculate a new subtraction, which would influence their gait during stair descent. Secondly, we used IA to represent DGS. Other potential indicators, such as the largest Lyapunov exponent or margin of stability, could also be considered for evaluating DGS during gait descent. It is important to mention that IA is one of many possibilities. Lastly, the participants carried a glass with 350 ml of water for MT. They had to use a cautious gait strategy and improve their DGS to avoid spilling water rather than to prevent a fall. Perhaps carrying a box or a tray might be a better option.

5. Conclusions

This study examined the effects of a concurrent cognitive or manual dual-task on gait velocity and DGS during stair descent. Gait velocity decreased under concurrent cognitive and manual dual-tasks. DGS decreased with increasing gait velocity during stair descent. Finally, the influence of gait velocity should be considered when assessing the effects of dual-tasks.

Author Contributions: Conceptualization, Q.S. and L.L.; Methodology, Q.S., W.S.; Resources, C.Z. and W.S.; Validation, W.S., C.Z. and M.M.; Formal analysis, Q.S., M.M.; Data Curation, Q.S., W.S. and C.Z.; Writing—original draft preparation, Q.S.; Writing—review and editing, L.L. and M.M.; supervision, L.L.; Project administration, L.L.; Funding acquisition, Q.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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